Nitrous oxide emissions from Canadian agroecosystems: Understanding the process

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Executive Summary

Nitrogen, an essential requirement of all living organisms, is fixed from the atmosphere during the preparation of commercial fertilizers, and by specialized plant-microbe associations. Biologically fixed nitrogen is immediately incorporated into the structural and functional components of the plants and microbes. This organic N will be released into the soil environment as ammonium (NH_4^+), when the plants and microbes die and decay. Most of this free NH_4^+ will be rapidly converted (nitrified) to nitrate (NO_3^-). Commercially prepared fertilizer-N is added to the soil as NH_4^+ or NO_3^-, which is collectively referred to as inorganic N. Plants and microbes can take up either form of inorganic N and convert it back into organic forms. Nitrogen may cycle between organic and inorganic form many times before it is lost from the soil-plant system. If conditions are favorable, NO_3^- can be converted (denitrified) to N_2 and returned to the atmosphere, closing what is essentially a continuous loop between the atmosphere and the soil-plant system. Nitrification and denitrification are integral and essential components of the nitrogen cycle. Nitrous oxide (N_2O) is released during both nitrification and denitrification. Its occurrence, therefore, is an unavoidable consequence of naturally occurring soil processes.

The magnitude of N_2O released from the soil-plant system is determined both by the amount of N that is nitrified and denitrified, and by the amount of N_2O that is generated per unit of N processed. The rate of nitrification and denitrification is determined largely by the availability of the raw materials required for the respective processes. Nitrification requires molecular oxygen (O_2), carbon dioxide (CO_2) and NH_4^+, while denitrification requires NO_3^- and a source of carbon (C). The absence of one or more of the required raw materials will limit or preclude the process. CO_2 is rarely, if ever in short supply within the soil environment. N_2O production, then, is controlled primarily by the supply of N, C and O_2. Increasing supplies of N and C generally increases the production of N_2O. The response to O_2 supply is a more complex matter. Nitrification is inhibited by limited O_2 availability. Conversely, denitrification is rapid when O_2 is limited. In addition, the yield of N_2O during both processes is strongly dependent upon available O_2. Like all biological processes, nitrification and denitrification also require favorable pH, temperature, and moisture conditions.

The magnitude of N_2O flux may vary by an order of magnitude over distances of just centimeters. This extreme variability has confounded attempts to establish clear relationships between point measurements of N_2O flux and the controlling factors. In the field, conditions controlling N_2O production at the microscale are established by an integration of many regulating variables operating at much larger scales. O_2 availability, as an example, is strongly affected by soil-water content. Soil-water content, in turn, is determined by precipitation, soil texture and structure, drainage, and slope position. Several landscape-scale studies have identified strong relationships between the magnitude of annual N_2O loss and differences in soil texture and drainage. An appropriate suite of landscape-scale indicators that can be used to estimate N_2O losses from agricultural lands in Canada has yet to be determined.

Studies comparing N_2O emissions from cultivated sites and adjacent undisturbed areas, indicate that agricultural activities generally increase total N_2O flux to the atmosphere. Agricultural activities impinge directly upon the factors controlling N_2O emission. The application of commercial N fertilizers, organic amendments, and growing pure stands of legume crops not only increases the amount of N cycling through the soil-plant system but also its pattern of availability. The release and uptake of N in undisturbed ecosystems is generally in close synchrony, and N_2O losses are minimal. In agroecosystems accumulations of inorganic N commonly occur after the application of N fertilizer or manure, and the plow down of legume residues. When this coincides with high soil-water contents and C availability substantial losses of N_2O can result. Particularly high losses of N_2O have been measured following applications of manure and legume residues. In addition to supplying available N, manure and legume residues also provide a ready supply of C. A few studies have indicated, however, that N_2O loss from standing forage or grain legumes is actually lower than other grain crops. This suggests that the handling of legume residues may be the critical consideration.

Most studies have reported increases in N_2O emissions as a result of fertilizer N, with the reported losses ranging between 1 and 3% of applied N. The relationship between fertilizer N rate and N_2O emission is not necessarily linear, but depends upon many other factors. For example, relative losses tend to increase with increasing clay content and are greater on sites with impaired drainage. In addition, losses of N_2O per unit of N applied are assumed to be greatest from anhydrous ammonia, lowest from NO_3^- based fertilizers, and intermediate for other N-fertilizers forms. The interaction between site-specific characteristics and the management of fertilizer-N is not well established. Very few studies have quantified N_2O losses according to fertilizer source, and their applicability to Canadian conditions is highly speculative.

Several studies have shown that losses of N_2O from N-fertilizers are particularly enhanced under zero till systems. Preliminary work from South Dakota suggests that careful placement of fertilizer-N can mitigate the increased losses from zero till. In addition, workers in the Alberta Parkland region found that losses of N_2O were actually lower on zero compared to conventional till systems during the spring thaw period. When these results were factored into annual loss estimates, there was no significant difference between the two systems. A better understanding of the interaction between tillage, N application, and N_2O emissions is required before an accurate assessment of zero or minimum till systems can be made.

Agricultural crops frequently take up 50% or less of fertilizer N applied. The fate of the remaining N remains unclear. Since the total N level of most soils does not appear to be increasing, most of this N must be moving off-site. Considering the tonnage of N fertilizers applied to agricultural lands each year, the consequences of losing even a fraction of this N as N_2O would be enormous.

N_2O emissions are highly episodic, being associated with high soil-water contents following precipitation events or melting of the snow-pack in spring. The confluence of regional precipitation and temperature regimes produces regionally distinct seasonal distributions of N_2O flux. In Quebec, where heavy snow accumulations insulates the soil and maintains surface temperatures near 0 _C, continuous and substantial N_2O emissions have been recorded throughout the winter. In the Alberta Parkland region, where less snow accumulates and surface soil temperatures hover below -5 _C, no N_2O emissions have been recorded during the winter

period. Episodic N_2O fluxes have been reported during the winter months for southern Alberta, coinciding with Chinook events that increased surface soil temperatures to +10 _C or higher. These seasonal patterns are important to recognize not only for quantifying annual N_2O losses, but also for assessing the impact of agricultural activities on those losses.

Opportunities for limiting agricultural emissions of N_2O revolve around the careful matching of fertilizer N application to crop needs, and the timing of those applications to match crop uptake patterns. Fertilizer-N placement has been shown to increase crop uptake, and appears to be a promising avenue for limiting N_2O emissions. Advanced N management techniques such as timed release fertilizers and nitrification inhibitors, also show promise. Avoiding practices, such as summer fallowing and fall plow down of legume residues, that increase NO_3^- accumulations prior to spring thaw could have a significant impact.

We have identified several gaps in our knowledge that need to be addressed: i) determine the impact of fertilizer form and placement, legume crops, and tillage systems on N_2O emissions with particular attention given to possible interactions between these management variables; ii) quantify N_2O emissions resulting from manure handling and application; iii) understand the controls and mechanisms of spring thaw and overwinter emissions; iv) partition the sources (nitrification, denitrification, and/or others) of N_2O emissions; v) determine the ratios of N_2O produced per unit of NH_4^+ nitrified or NO_3^- denitrified; vi) quantify agricultural contributions to off-site N_2O emissions; vii) refine our understanding of N cycling within agroecosystems in order to increase N uptake efficiencies.

Background

Nitrogen is essential for the growth and maintenance of all living organisms. Soil microorganisms not only require nitrogen for their structural and functional components, but many also gain energy by transforming it from one chemical form to another. Nitrogen, therefore, undergoes a multitude of transformations and is found in a variety of forms within the plant-soil-atmosphere system. Nitrous oxide (N_2O) is generated as an end- or by-product during many of these transformations. The emission of N_2O from agroecosystems to the atmosphere, is the unavoidable consequence of naturally occurring processes.

The amount of N_2O produced during most of these processes is negligible. Nitrification and denitrification are exceptions. For the purposes of this discussion, nitrification will be defined as the conversion of ammonium (NH_4^+) to nitrate (NO_3^-) and denitrification as the conversion of NO_3^- to molecular nitrogen (N_2) or N_2O. These two processes are considered to be the source of nearly all the N_2O released to the atmosphere by agroecosystems. A third process, chemodenitrification, can generate significant amounts of N_2O, but will occur only under very specific conditions. Chemodenitrification has not been shown to be a significant contributor of N_2O from agroecosystems, and will not be considered further in this discussion.

The passage of nitrogen through the soil-plant-atmosphere system is cyclical in nature, and can be depicted as a "loop within a loop" (Fig. 1). The outside loop consists of the gaseous exchange of nitrogen between the atmosphere and the soil-plant system. Atmospheric N_2 enters the soil-plant system after being fixed (converted into a biologically available form) via specialized plant-microbe associations or the production of commercial nitrogen fertilizers. Biologically fixed nitrogen is immediately incorporated into the structural and functional components of the plants and microbes. This organic N will be released (mineralized) into the soil environment as NH_4^+, when the plants and microbes die and decay. Most of this free NH_4^+ will be rapidly nitrified to NO_3^-. Commercially prepared fertilizer-N is added to the soil as NH_4^+ or NO_3^-, which is collectively referred to as inorganic N. Inorganic N from commercial fertilizer is indistinguishable from the inorganic N released during decomposition of plant or animal matter. Plants and microbes can take up either of these N forms, however the nitrification process is sufficiently rapid that most of the NH_4^+ will be first converted to NO_3^-. Some N will be returned to the atmosphere at this point, as N_2O is produced during nitrification, and, depending upon conditions, some portion of the NO_3^- may be denitrified to N_2 or N_2O. The largest proportion of the inorganic N will, however, be taken up and transformed into organic forms by plants or microbes. When the organisms die and decompose, N will again be mineralized. The transfer of N between organic and inorganic forms constitutes the inner loop of the N cycle. Organic forms of N are not susceptible to loss as N_2O. The amount of N_2O produced within an agroecosystem is related to the amount of inorganic N available, the amount of inorganic N being taken up by plants or microbes, and the status of the environmental conditions controlling these processes.

Controls on N_2O Flux

Firestone and Davidson (1989) used a "hole-in-the-pipe" analogy to represent the control of N_2O emissions from soils (Fig. 2). The amount of N_2O produced is not only a function of how many units of N move through the pipes, but also the yield of N_2O per unit of N (i.e. how big the holes in the pipes are). The amount of N moving through the pipe is governed both by the amount of inorganic nitrogen (NH_4^+ and/or NO_3^-) available and the rate at which nitrification and denitrification proceed. The amount of inorganic nitrogen available at any point in time is a reflection of atmospheric deposition and commercial fertilizer

applications, and by the rate that the organic N, bound up in plant residues, animal manures, and soil organic matter, is converted to inorganic form (i.e. mineralization).

The processes of mineralization, nitrification, and denitrification are carried out by microorganisms. Therefore, it is the conditions at the cellular or microscopic scale that directly control the processes. For mineralization these include the type and amount of available carbon (C), and the supply of O_2, for nitrification these include, NH_4^+, O_2, and carbon dioxide, while for denitrification these include soluble C and NO_3^-. Denitrification is inhibited by the presence of O_2; thus the supply of O_2 is a critical factor for all three processes. In addition to the supply of raw materials, microorganisms also require favorable environmental conditions such as appropriate pH and adequate moisture and heat. The relationship between N_2O flux and the supply of raw materials has been convincingly demonstrated under laboratory conditions. Similar relationships have not been as easily established in the field. N_2O emission rates may vary by an order of magnitude over distances of just centimeters. Statistically significant relationships between N_2O emissions and soil concentrations of NH_4^+, NO_3^-, and/or available C have been reported, however the strength of those relationships has generally been weak and the relative importance of the factors has not been consistent.

The failure to establish clear and broadly applicable relationships between point measurements of N_2O flux rates and specific soil parameters can be explained, at least in part, by referring back to our "hole-in-the-pipe" analogy. Firstly, N_2O can arise from two simultaneous processes, the rate of each process being determined by different factors, or in the case of O_2, responding differently to the same factor. Secondly, the amount of N_2O produced is not only a reflection of the rate (amount of N moving through the pipes) of these processes, but also of the yield of N_2O per unit N (the size of the holes). The ratios of N_2O to NH_4^+ nitrified or NO_3^- denitrified, are governed by another related but distinct set of variables. Thirdly, there is often a disparity of scale between point measurements of N_2O flux and soil parameter measurements. The microbes producing N_2O are responding to conditions that may vary over scales of micrometers or millimeters. Determinations of soil parameters such as NO_3^- or NH_4^+ concentrations are made on bulk soil samples, resulting in "averaged" values for soil volumes in the centimeter range or beyond. Lastly, N_2O produced within the soil profile is not instantaneously emitted from the soil surface. There can be a considerable time lag between production and emission. In addition, production rates are not linearly related to emission rates since the N_2O produced can be further reduced to N_2 during transport to the soil surface.

In the field, conditions at the cellular level are determined by an integration of many regulating factors. O_2 status is a good example. O_2 is delivered to the cell surface in solution, therefore a critical supply of water is required. However O_2 travels much more slowly through water, therefore when the water content of the soil is too high O_2 movement from the atmosphere to the location of the cell will be restricted and O_2 dependant processes will be inhibited. The amount of O_2 that can be dissolved in the soil solution is strongly influenced by temperature; thus temperature not only influences the rate of the process directly but also the supply of O_2. How rapidly the soil delivers O_2 is largely determined by its porosity, which in turn is determined by texture and structure. Robertson (1989) developed a conceptual model of the factors controlling nitrification and denitrification (Fig. 3 & 4). Factors exerting direct control at the cellular level are termed proximal, while factors that modify or regulate conditions at the cellular level are referred to as distal. Distal factors are arranged in levels or classes, with a hierarchy of importance established within each class. Different levels or classes loosely correspond to scales of observation. The model underscores the importance of considering regulating (distal) factors that are appropriate to the scale of investigation. Relatively strong relationships have been identified when seasonal or cumulative N_2O emissions are compared to variations in soil-water, inorganic N or available C. Lemke et al. (1998a) were able to explain

more than 80% of the variability in cumulative N_2O loss during spring thaw by differences in mean pre-thaw soil inorganic N concentrations. During the frost-free period, greater than 70% of the seasonal variability in N_2O emissions could be explained by mean soil NO_3^- and water-soluble C concentrations. Groffman and Tiedje (1989) were able to explain 86% of the landscape scale variability in annual denitrification activity by differences in drainage and texture. Factors such as soil porosity, drainage and slope position, are stable over time and vary spatially in a quantifiable fashion. Factors such as these show good promise for use in models to predict N_2O emissions at the landscape scale.

Climatic factors

Precipitation

N_2O emissions during the growing season are episodic, and are usually associated with periods of high soil-water content after rainfall or irrigation. Precipitation or irrigation increases the soil-water content resulting in low air-filled porosity and limited O_2 availability and favours denitrification. N_2O emissions are particularly intense after wetting of a dry soil. Bursts of respiratory activity after the wetting of a dry soil is a well documented phenomena, and appears to be related to increased C availability. Increased respiration generally indicates higher mineralization rates of N, and could translate into optimal nitrification rates in well aerated portions of the profile. The increase in O_2 consumption would also favour the development of anaerobic sites in other portions of the soil profile, and this, in combination with the favourable supply of NO_3^- and C, would promote denitrification. The intensity of respiration after wetting/drying events tends to decrease as the frequency of the events increases. This may partially explain the smaller N_2O emissions after precipitation as the growing season progresses.

Considering that N_2O emissions are associated with high soil-water contents, we would anticipate that agricultural regions receiving higher rainfall would have proportionately higher N_2O emissions. These comparisons are, however, confounded by differences in site-specific regulators of soil-water status, such as slope position, soil texture, and drainage. Workers in Saskatchewan have shown that slope position in hummocky terrain is a strong controller of N_2O emission rates (Corre et al. 1996). Workers in the parkland region of Alberta have found that differences in N_2O emission rates between slope positions located within tens of meters was greater than the differences between sites separated by a hundred kilometers or more (Lemke et al. 1998b). The latter workers found a strong correlation between N_2O loss and soil texture for sites having similar slope positions. In general, soils with coarse textures have better drainage, higher air-filled porosity, and better O_2 status than fine-textured soils. N_2O emission research has often focused on fine-textured soils where conditions are more favorable for denitrification. However, more recent work suggests that these soils may not be the greatest source of N_2O, as a large fraction of the denitrified N is reduced completely to N_2. The contribution of lighter soils which would yield more N_2O per unit of N denitrified may be underestimated, especially those under crops receiving high N rates or animal manure.

Temperature

As with all biological processes, nitrification and denitrification are also highly dependent on temperature. Some authors have reported the lower limiting temperature for denitrification to be 0 °C or less, while others have observed no denitrification in soils at 5 °C or below. These inconsistent results could be due to the capacity of denitrifiers to adapt to environmental temperatures, or to temperature-induced shifts in the structure of the soil denitrifier community. Emissions of N_2O observed during springtime in temperate climates when most of the environmental factors are optimal for denitrification, except for temperature, strongly suggest that denitrification is not negligible at low temperatures. In fact, measurements near Québec city indicated that winter and spring melt N_2O-N losses from barley cultivated soils, even under snow cover, make up a significant part of the annual N loss (van Bochove et al. 1996). The Québec region

has a continuous snow pack up to a meter deep through most of the winter period. This snow pack buffers air temperature extremes, and soil surface temperatures hover between 0 and 2 _C. Denitrifying enzyme activity (DEA) measurements suggest that the highest potential for NO_3 reduction was near the surface of this agricultural soil, even though higher N_2O concentrations were found deeper in the B horizons. The higher N_2O concentrations in the lower soil horizons could be explained by positive temperature gradients with depth which resulted in decreased gas solubility and the degassing of N_2O. However, the higher N_2O concentrations could also be explained by variations in the expression of N_2O reductase with depth which can modify the N_2/N_2O ratios in relation to the availability of O_2. Calculated N_2O-N fluxes showed that N losses by gaseous emissions from soils during winter and spring were comparable to, or exceeded, similar reported N losses during the growing season. Moreover, N_2O fluxes were far greater from an agricultural soil than from a control forest soil.

In contrast, investigators in the Edmonton region did not detect N_2O emissions during the winter months. This region maintains a continuous snow pack that is 10 to 30 cm in depth. Thus the soil in this region is not as well insulated, and soil temperatures hover below −5_C through much of the winter period. Temperatures in this range likely preclude microbial activity at or near the soil surface. When soil temperatures approached or exceeded the freeze point at spring thaw, however, very high N_2O emissions were measured. Cumulative N_2O emissions during spring thaw represented as much as 80% of estimated annual N_2O loss.

Southern Alberta experiences a series of Chinook events during the winter months. The snow pack is discontinuous, and the soil is poorly buffered from temperature extremes. Soil surface temperatures can range from +10 to −20 _C. N_2O emissions during the winter period in this region are episodic in nature, being associated with Chinook events when soil surface temperatures climb into the thawing range. Cumulative N_2O emissions during the winter and spring thaw can represent 50% or more of the estimated annual N_2O loss (Chang et al. 1998).

Freezing and thawing cycles have been shown to induce soil physical and biological changes such as disruption of structure (aggregate stability) and stimulation of denitrification. The increase in N_2O emissions following freeze-thaw cycles may be attributed to the diffusion of newly available organic substrates from disrupted aggregates to denitrifying micro-organisms. Conditions established during the previous growing season also appear to have a strong influence on the magnitude of cumulative N_2O loss during the winter and spring thaw. Van Bochove et al. (1996) observed that highest winter fluxes coincided with high soil-water contents in the preceding fall. Lemke et al. (1998a) were able to explain more than 80% of the variability in cumulative N_2O loss during spring thaw by differences in pre-thaw soil inorganic N concentrations.

Agricultural Managements

Agricultural management practices potentially influence the magnitude and distribution of N_2O emissions in numerous ways. Tillage and wheel traffic can alter soil structure, bulk density, and the continuity of pore channels. These, in turn, strongly influence soil moisture and aeration status, and the uptake and release of soil C and N. The consecutive applications of commercial fertilizers or organic amendments can alter soil pH. The growth patterns of annual grain crops results in considerable periods of time during spring and fall when mineralization processes are active but vegetative growth is not. If the resulting accumulation of N and C coincides with high soil-water contents, the potential for increased N_2O emission is great. The application of fertilizer N, growing pure stands of legumes, and the application of livestock manure directly affects the proximal factors controlling N_2O production by increasing the input of N and C. The latter management practices are considered to have the most impact on N_2O emissions.

N fertilizers

The application of N fertilizer affects N_2O emissions by adding nitrate and/or ammonium to the soil system. This means that more N will be available for nitrification and denitrification and more N_2O will likely be produced and emitted. The direct contribution of N_2O from N fertilizers appears to range from 0-3% of added N, although losses as high as 24% have been reported. Direct contribution is calculated as the difference in N_2O emitted from plots with and without N fertilizer additions. While most studies have reported some increase in N_2O emission as a result of fertilizer N, the relationship between fertilizer rate and N_2O emissions is not necessarily linear. In fertilized soils, N_2O production and emission can be can be limited by C rather than N, and is strongly associated with precipitation events. Low N_2O emissions following addition of as much as 150 kg N to a soil with low available C have been observed (Rochette et al. 1998). When N is applied in the spring, most of the emissions are observed in the two months or so following application when N and C are more abundant (Lessard et al. 1996).

Fertilizer type: The form in which fertilizer N is applied to the soil may affect N_2O loss. Losses are presumed to be greater from NH_4^+ than from NO_3^- based fertilizers since the NH_4^+ molecule undergoes an additional nitrification step, before becoming susceptible to losses via denitrification. Particularly high losses have been reported after anhydrous ammonia applications, however the reason for this difference is not well understood. Higher losses of N_2O can occur from NO_3^- based fertilizers however, if they are applied when (or just prior to) soil conditions favor denitrification. One example is the lower N recoveries from fall applied NO_3^- compared to NH_4^+ based fertilizers reported in the Alberta Parkland region (Malhi and Nyborg 1983). The NO_3^- based fertilizers are more susceptible to loss via denitrification during the following spring thaw when conditions favor denitrification. The impact of fertilizer type on N_2O emission may be of particular importance for western Canada where anhydrous ammonia is used extensively. For example, total tonnage of fertilizer N sold in Canada during the 1995/96 crop year was approximately 1,600 kt. If we assume a 1.25% yield of N_2O-N per unit of N applied the N_2O-N emitted would total 20 kt. If we assume an additional 1.0% yield from the 530 kt which was applied as anhydrous ammonia, the total becomes 25.3 kt. This represents an almost 30% increase. We are not aware of Canadian research that has expressly compared the impact of different N-fertilizer forms, particularly anhydrous ammonia, on N_2O emissions.

Mode and timing of application: It is reasonable to assume that if N is applied when and where plants need it most, nitrogen-use efficiency will increase, there will be less free N in the soil for shorter periods of time, and N_2O emissions will be minimized. Placing fertilizers into bands or nests has been shown to increase fertilizer use efficiency, however concentrating fertilizer into bands can cause localized soil pH alterations which might increase the ratio of N_2O produced to N nitrified and/or denitrified. Thus total N_2O emitted could increase despite decreases in the overall loss of N.

Slow release or coated fertilizers are also being tested to better synchronize fertilizer N release and crop uptake. Webb et al. (1997) found that N_2O emissions were reduced by as much as 90% when sulfur coated urea was used on turf grass. Delgado and Mosier (1996) found that N_2O emissions were 35% lower from irrigated spring barley plots receiving polyolefin coated urea compared to those receiving urea. In the same study, dicyandiamide (a nitrification inhibitor) reduced N_2O emissions by 81%. Bronson et al. (1992) evaluated the use of several different nitrification inhibitors and found that N_2O emissions were reduced by between 40 and 70 % from irrigated wheat and corn crops. We are not aware of Canadian studies which have specifically addressed the impact of placement and timing of N-fertilizers on N_2O emissions from agricultural soils.

Crop residues

The crop residues that are returned to the field contain organic N. When this organic N is mineralized by decomposers, it is available for nitrification and denitrification and losses of N_2O can occur. The timing of this release is largely governed by the C/N ratio of the crop residue, as well as its timing and placement. Legume residue likely induces greater losses of N_2O than a comparable amount of cereal or other grain crop residue since legume residue generally has a low C/N ratio and more N will be released into the environment during decomposition. The C content of crop residues will also stimulate soil respiration and O_2 consumption. In a laboratory incubation study, DeCatanzaro et al. (1987) found that 10 g of alfalfa residue stimulated soil respiration as much as 100 g of wheat straw, indicating the much greater accessibility of C in alfalfa residue. Thus the decomposition of legume residue will not only supply greater amounts of N, but will also more strongly stimulate O_2 consumption and provide a more readily accessible C source for soil denitrifiers than other crop residues. All legume crops do not yield the same amount of residue and their N content may also be different. For example, grain legumes will produce residues that contain less N since a large fraction of the plant N has been concentrated in the harvested grain. In contrast, when a legume forage crop is plowed under to plant an annual crop in the rotation, a much larger amount of organic N is added to the soil.

The critical question is not only the amount of N supplied by the crop residue, but when that N becomes available in relation to crop uptake and the status of the other variables controlling N_2O emission. If the N release from crop residues results in a pool of free mineral N at a time when C and soil-water content is high, significant losses of N_2O may occur. Fall plough down of alfalfa is an excellent example. Wagner-Riddle et al. (1997). reported greater losses of N_2O during the spring thaw period following plow down of an alfalfa stand compared to a fallow treatment. Similar observations have been made in western Canada where N_2O emissions from alfalfa plots were an order of magnitude greater than wheat stubble plots, both of which had been cultivated in the fall (R.L. Lemke, unpublished data). Fall incorporation of the alfalfa resulted in elevated soil NO_3^- concentrations during the following spring when the soil surface was at or near saturation and available C was favorable.

Biological fixation

Biological fixation of N represents a significant input of N into agricultural soils. Most of this N will eventually be nitrified or denitrified. N-fixating bacteria can also denitrify and produce N_2O. The International Panel on Climate Change (IPCC) inventory methodology uses a coefficient of 4 kg N_2O-N ha^{-1} yr^{-1} for each hectare of legume crop. These losses are attributed both to denitrification by Rhyzobia in the root nodules, and during the decomposition of the crop residues. The impact of legume residues has been discussed in the previous section. These authors are not aware of any studies that have attempted to partition N_2O emissions measured from legume crops into N_2O arising from N cycling and N-fixation. The significance, if any, of N_2O arising from the fixation process is unknown. Mackenzie et al. (1997) reported higher N_2O emissions from standing corn as compared to alfalfa or soybean. Burton et al. (1997) reported lower surface emissions from standing alfalfa compared to fallow plots. The latter workers noted that greater production of N_2O occurred in the soil profile under alfalfa, but at a greater depth. This N_2O must be transported through the soil profile prior to emissions to the atmosphere, providing more opportunity for the further reduction of N_2O to N_2. Established forage stands utilize more soil water and have a longer period of active growth than spring seeded grain crops. Thus aeration and N availability may be less favorable for N_2O production. As already noted, the incorporation of legume residue can result in significantly increased emissions of N_2O, but this increase may be off-set by lower losses noted during other phases of the rotation. Accurate evaluation of N_2O emissions from legume crops must include all phases of the rotation, and carefully consider the placement and timing of crop residue incorporation.

Manure application

The application of manure to soil can lead to a substantial production of N_2O. Inorganic N in manure is largely in the ammonium form (all of it in slurries) and is rapidly nitrified in the soil. In addition to supplying large amounts of N which increase the NO_3^- pool, manure supplies a lot of easily decomposable organic substrates that can both sustain denitrification and induce anaerobiosis due to a high biological O_2 demand. In 1991, 22,000,000 Mg of manure were produced in the province of Québec alone. This is equivalent to approx. 117,000 Mg of N and potential emissions of 1800 Mg of N_2O-N (1% of total N). Manures are clearly an important potential source of N_2O emissions in eastern Canada. Farmers empty their storage facility in the spring and in the fall by applying the manure to their land. High emissions of N_2O have been reported following manure application to agricultural soil in Ontario and Québec. Solid cattle manure applied in the spring to a maize crop has produced N_2O emissions that were similar to a heavily fertilized control. Liquid hog manure, on the other hand, has resulted in emissions that were 10 times larger than the fertilized control in a soil where easily-decomposable C was low. Fall application could potentially induce large N_2O emissions by adding C and N to the soil just before winter when it has been shown that denitrification was active and is currently under investigation. Chang et al. (1998) demonstrated that land-application of feedlot manure has a cumulative effect. N_2O emissions from field plots which had received 21 annual applications of feedlot manure ranging from 0 to 180 Mg ha^{-1}, were increased from less than 1 kg N ha^{-1} to 56 kg N ha^{-1} respectively.

Soil Management

Tillage can have a strong impact on the N cycle by affecting the aeration, temperature and humidity of soils, and by modifying soil structure and the distribution of fertilizer, crop residues and organic amendments in the soil profile. Both nitrification and denitrification can be affected. It is not clear if the net effect of tillage on N_2O emissions is significant. A number of studies have reported higher losses of N_2O from no-till (NT) compared to conventional-till (CT) systems. However, recent studies in southern Ontario (C. Drury, unpublished data) and in north-central Alberta (Lemke et al. 1999) have reached opposing conclusions. Previous studies comparing tillage systems generally included only the frost-free period. Lemke et al. (1999) reported significantly higher N_2O emissions from CT compared to NT plots during the spring thaw period. When the spring thaw emissions were factored into the estimates of annual N_2O emissions, losses from NT were equal or less than those from CT. There appears to be a significant interaction between fertilizer placement and tillage regime. Hilton et al. (1994) compared N_2O emissions from surface applied ammonium nitrate and injected urea-ammonium nitrate solution on plots under NT and plots tilled with a moldboard plow. Surface applications resulted in significantly higher N_2O emissions from NT when compared to ploughed plots, but NT plots receiving injected N had emissions that were comparable to surface applied ploughed plots. The authors note that defining what is meant by "no-till", "minimum tillage", and "conventional till" is an important point to consider, as these often have different definitions in different regions of the country.

Summerfallow

Summer fallowing is a common management practice in the semiarid region of the Canadian prairie. The increase in soil-moisture coupled with the accumulation of soil NO_3^- that generally accompanies a fallow period would be expected to increase N_2O production and emission. In Saskatchewan, Aulakh et al. (1984) reported significantly higher N_2O emissions from fallow compared to fertilized spring-wheat treatments during the growing season. Lemke et al (1999) reported lower losses from fallow compared to fertilized spring-wheat treatments in the Parkland region of Alberta during the growing season, but losses were frequently higher during the following spring thaw. Wagner-Riddle et al. (1997) also reported higher annual losses of N_2O from fallow compared to cropped treatments. These few studies support the

expectation that fallowing can lead to increased N_2O production.

Irrigation

The impact of irrigation on N_2O emissions would largely approximate that of rainfall (see section on climatic factors). Irrigation-induced N_2O emissions will likely vary during the growing season depending on the status of other controlling factors (N or C availability). The increased production potentials and the fact that irrigated acreages are often utilized for high value specialized crops (potato, strawberry, tobacco, vegetables), translates into higher per hectare inputs of fertilizer N. In addition, the irrigation district of southern Alberta is home to a large intensive livestock industry. The combination of higher N inputs from fertilizers and/or the land application of livestock manure represents a considerable potential for both direct and indirect emissions of N_2O. We are not aware of studies specifically addressing the influence of irrigation on N_2O emissions in Canada.

Organic Soils (Histosols)

The IPCC National Gas Inventory Methodology identifies the cultivation of organic soils as a potentially very high source of N_2O. This possibility is based on a couple of studies and the fact that these soils are rich in N. We are not aware of studies aimed at quantifying N_2O production and emission resulting from the cultivation of Histosols in Canada.

Off-site Emissions

Frequently, less than 50% of applied fertilizer-N is taken up by agricultural crops. N-cycle studies on agricultural crops typically fail to close the N budget. A significant fraction of the N added (up to 40%) is often not accounted for and assumed to be lost to the environment. Part of the N that is not used by plants can be denitrified to N_2 on-site, but some may also be transported "off-site" across the boundaries of the agricultural ecosystems. This lost N can be in solution (NO_3^-, N_2O, and organic N in drainage water), bounded to soil particles (wind or water soil erosion) or volatilized (mostly NH_3). It may be exported to non-agricultural ecosystems where it can be nitrified or denitrified and produce N_2O. Current estimates suggest that 0.75% of added N is emitted as N_2O off-site. Considering the amount of fertilizer N applied annually, only a small portion of the unaccounted N needs to be lost as N_2O to have a major impact on atmospheric N_2O concentrations (Robertson 1993). Accounting for off-site emissions poses a formidable challenge. N exchange between agroecosystems and their environment is not a one-way flux. Atmospheric deposits leave as much as 35 kg N ha^{-1} yr^{-1} on agricultural fields in Southern Ontario, but only 5 kg N ha^{-1} yr^{-1} on the prairies. All inputs as well as losses would have to be quantified.

Mitigation Options

Proposed mitigation options center primarily around N-use efficiency, assuming that carefully matching the rate and timing of N additions to crop requirements will reduce the amount of "free" N in the system and the potential for N_2O production. Advanced fertilization techniques such as controlled release fertilizers and the use of nitrification inhibitors appear to hold promise in this regard. N_2O emissions are strongly governed by slope position, drainage, and textural variations. Site-specific management techniques that adjust N inputs to account for some of these variations may also be a promising avenue. Winter and spring thaw emissions represent a significant proportion of annual N_2O emissions in most agricultural regions of Canada. A considerable reduction in emissions might be affected if strategies can be found to limit mineral N availability during this time period. Lastly, reducing fallow acreages should also produce a relative reduction in N_2O emissions.

Research Needs

N_2O emissions have not been convincingly partitioned between nitrification, denitrification, and/or other processes, nor can the ratios of N_2O produced per unit of N nitrified or denitrified be unambiguously established. These two fundamental inadequacies continue to confound attempts develop broadly applicable predictive models of N_2O emissions. More specific questions that need to be answered include: i) The impact of fertilizer type and placement on N_2O emissions, paying particular attention to anhydrous ammonia, and the possible interactions of fertilizer type, placement and tillage regime; ii) An assessment of N_2O emissions from legume crops, considering all phases of the rotation and paying particular attention to the timing of residue incorporation; iii) The impact of manure application to soil, including the effect of type of manure, dose and time of application; iv) The mechanisms and controls on N_2O emissions during the winter and spring thaw periods need to be established, and attention paid to the N_2O/N_2 ratio in soil profile; v) The factors that most strongly control N_2O fluxes at the field, landscape, and regional scales need to be identified; and vi) A more complete N budget for agroecosystems is required to quantify off-site contributions, and refine N management.

Summary

Nitrification and denitrification are considered the major sources of N_2O emissions arising from agricultural soils. The magnitude of N_2O produced is determined by the rate of nitrification and denitrification, and the ratio of N_2O produced per unit of N processed. How much of this N_2O is released to the atmosphere also depends upon the amount of N_2O consumed during transport to the soil surface. The rates and ratios of N_2O produced are controlled at the cellular level by a complex interaction between O_2, NO_3^-, NH_4^+, available C, moisture, and temperature. In the field, conditions controlling N_2O production at the microscale are established by an integration of many regulating variables operating at much larger scales. Several landscape-scale studies have identified strong relationships between the magnitude of annual N_2O loss and differences in soil texture, drainage, and slope position, emphasizing the importance of selecting the appropriate indicators for the scale of the study. N_2O emissions are highly episodic, being associated with high soil-water contents following precipitation events or melting of the snow-pack in spring. The confluence of regional precipitation and temperature regimes produces regionally distinct seasonal distributions of N_2O flux.

Agricultural activities influence N_2O emissions primarily by changing the amount and pattern of N cycling through the soil-plant system. When accumulations of inorganic N, such as those following fertilizer N or manure application, legume residue incorporation, or fallow periods coincide with high soil-water contents and C availability, substantial losses of N_2O can occur. Particularly high losses of N_2O have been measured following manure and legume residue additions which increase available C as well as N. A few studies have indicated, however, that N_2O loss from standing forage or grain legumes is actually lower than from other grain crops. This suggests that the handling of legume residues is a critical consideration, and that all phases of the rotation must be considered. Most studies have reported increases in N_2O emissions as a result of fertilizer N, with the reported losses ranging between 1 and 3% of applied N. The relationship between fertilizer-N rate and N_2O emission is not necessarily linear, but depends upon many other factors such as site-specific characteristics, tillage, and the type and placement. Agricultural crops frequently take up 50% or less of fertilizer N applied. The fate of the remaining N remains unclear, but is of considerable concern since some fraction of this N is likely lost as N_2O. Opportunities for limiting agricultural emissions of N_2O revolve around the careful matching of fertilizer N application to crop needs, and the timing of those applications to match crop uptake patterns. A number of knowledge gaps that need to be addressed were identified.

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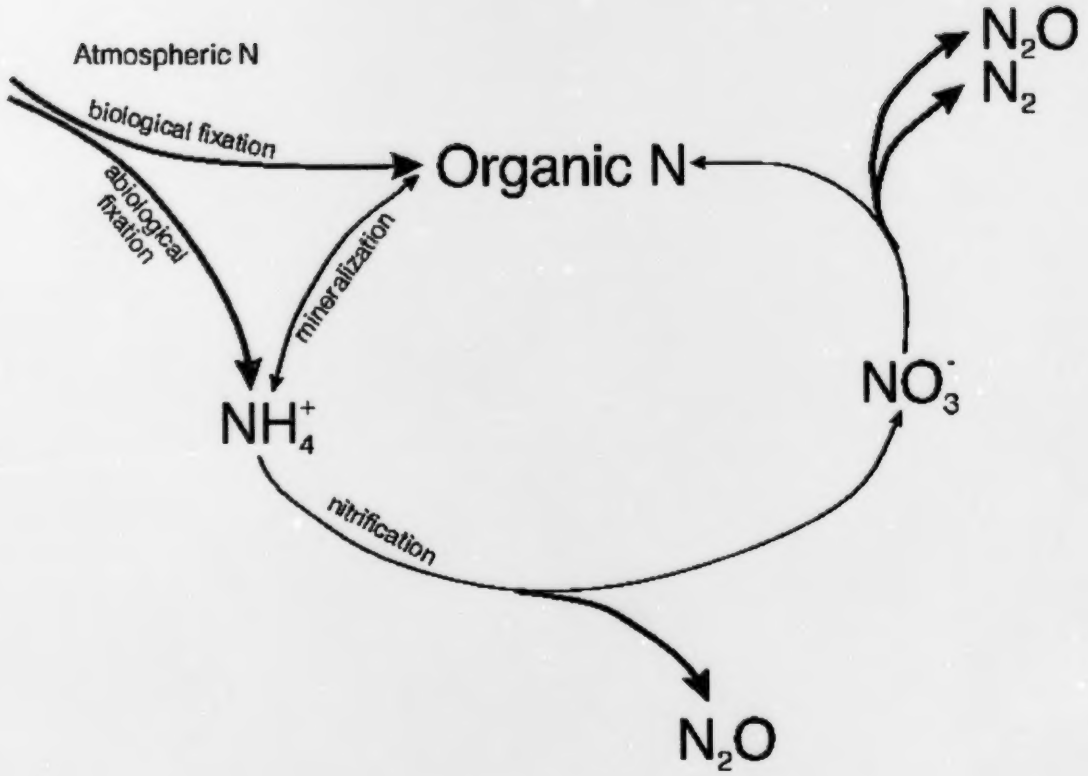

Fig. 1. Highly simplified representation of N cycle depicted as a "loop within a loop".

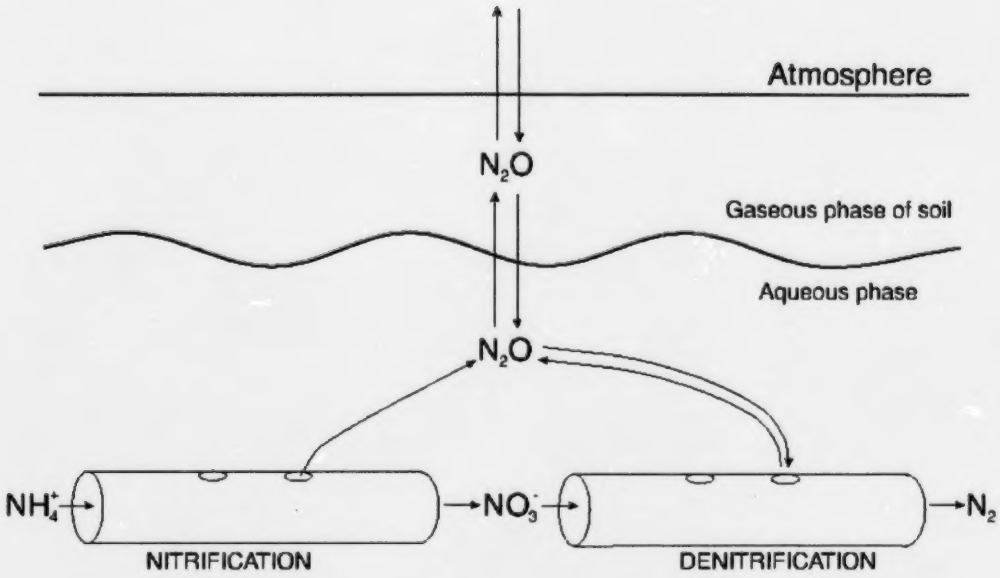

Fig. 2. Three levels of regulation of N2O flux: i) the rates of nitrification and denitrification; ii) the ratios of end products (the size of the holes in the pipes); and iii) diffusion and consumption of N gases prior to escape from the soil to the atmosphere (Firestone and Davidson 1989).

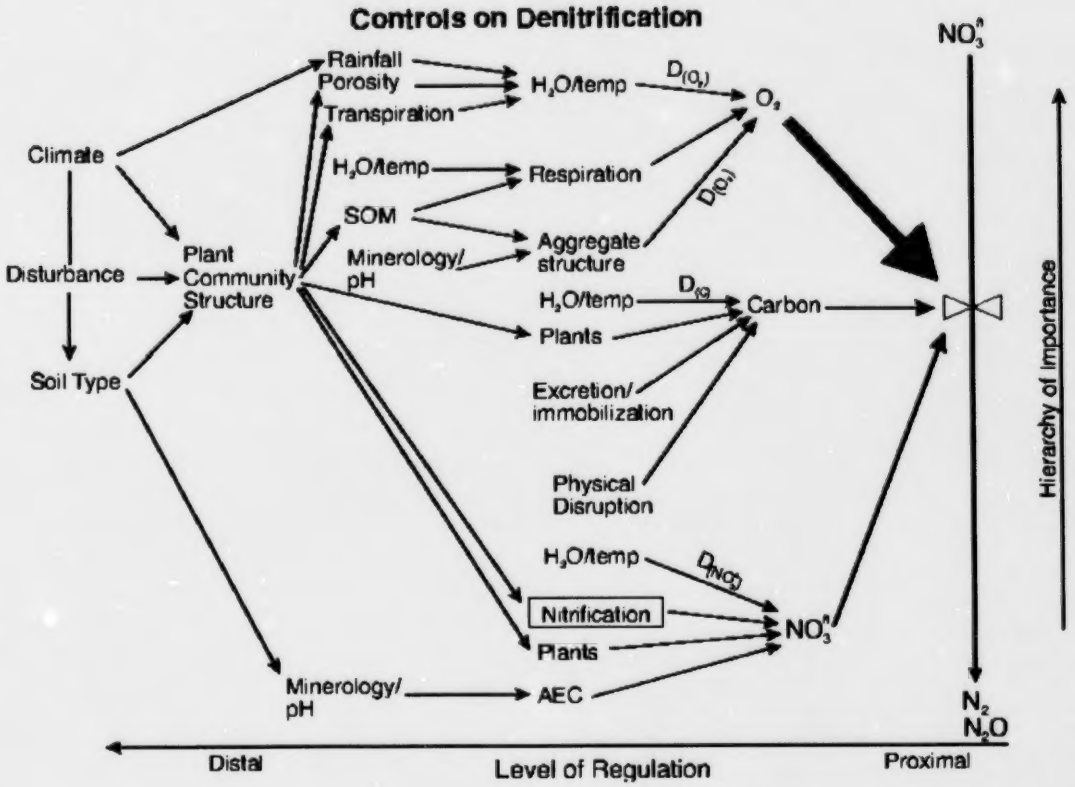

Fig. 3. Conceptual model showing relationships among the major controllers of denitrification in soil (Robertson 1989).

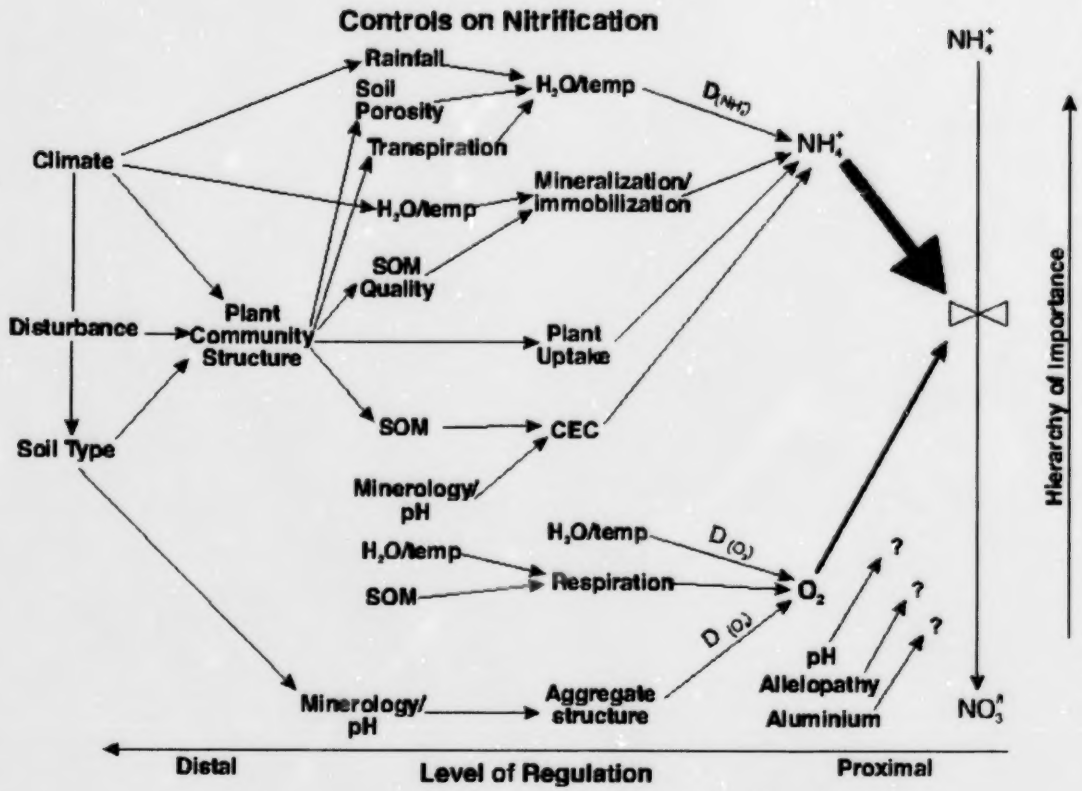

Fig. 4. Conceptual model showing relationships among the major controllers of nitrification in soil (Robertson 1989).